

# IoT Connectivity in Radar Bands: A Shared Access Model Based on Spectrum Measurements

Zaheer Khan, Janne J. Lehtomäki, Stefano Iellamo, Risto Vuohioniemi, Ekram Hossain,  
and Zhu Han

## Abstract

To address the challenge of more spectrum for the Internet of things (IoTs) connectivity, this paper proposes a shared access (SA) framework with rotating radars. The proposed framework is based on the results of our measurement campaign in which we measured spectrum usage patterns and signal characteristics of three different ground-based fixed rotating radar systems near Oulu, Finland. In our work, we review existing IoT protocols designed for the licensed or the unlicensed IoT access, and make the case that the existing protocols cannot be straightforwardly applied for SA in the rotating radar bands. We then present the benefits of using a zone-based SA method in rotating radar spectrum for the operators providing IoT services, and also highlight challenges in its implementation. To fully develop the considered zone-based SA method that ensures coexistence of IoT devices with no harmful interference to the rotating radars, we propose an Radio Environment Map (REM)-enabled architecture for the SA. The proposed architecture provides principles and rules for using the SA for the IoTs, and it does not require modifications in the incumbent radar systems.

## Index Terms

Internet of Things (IoT), radar bands, shared access, gateways, spectrum occupancy measurements, radio environment map (REM).

## I. INTRODUCTION

Two big waves in the wireless world—the exponential growth in data usage on smart mobile devices; and the continuous need of support for “new things” in the Internet Things (IoTs), poses new challenges for the design of fifth-generation (5G) wireless networks [1], [2]. IoT is regarded as the next stage in digital communications with a wide range of applications, such as tasked sensors, controllers, smart metering, security systems and industrial control. Traditionally, wireless operators have focused on building networks

Z. Khan, J. J. Lehtomäki, R. Vuohioniemi are with the University of Oulu, Finland, S. Iellamo is with Institute of Computer Science at FORTH, Greece, E. Hossain is with University of Manitoba, Canada, and Zhu Han is with University of Houston, USA.

This work was funded by Academy of Finland under the grant number 26687 and in part by a Discovery Grant from the Natural Sciences and Engineering Research Council of Canada (NSERC).

for smart mobile devices; however, to take into account the rise of IoT, wireless operators need to invest in networks and access models that are also fit for the IoTs.

Communication is the ‘glue’ that binds all the sensors, actuators, management platforms and databases together to form the IoTs. Wireless communications are the key to provide connectivity in the IoTs, and as a result IoT can further congest the wireless networks. For the regulators, this means freeing up more spectrum for wireless communications at a time when we are already running out of frequency spectrum [2], [3]. There is a plethora of new wireless technologies for IoT connectivity currently being developed. However, there is much uncertainty as to where spectrum might come from to efficiently support millions of connected devices once these technologies are deployed globally. The problem of spectrum scarcity due to the two big waves in the wireless world has triggered regulators’ interest in novel spectrum sharing mechanisms, which enable coexistence between distinct radio technologies and services. In terms of new spectrum sharing models, the potential use of shared access (SA) between radar and wireless communications systems has generated particular interest [4]. One reason for this interest is the fact that communications systems and radar systems jointly consume most of the highly desirable spectrum below 6 GHz [5], [6]. The appealing features of radar spectrum have already led some countries to open parts of the S (2 to 4 GHz) and C (4 to 8 GHz) bands for wireless broadband services.

To address the challenge of more spectrum for the IoTs, in this paper, we have identified the suitability of frequency spectrum used by the rotating radars for providing connectivity to the IoTs (sensors, actuators, and gateways) on the basis of a SA framework. Our contributions in this paper include the following:

- First, we present results of our measurement campaign in which we measured spectrum usage patterns and signal characteristics of different ground-based fixed rotating radar systems in Finland.
- Based on the measured/analyzed features of each radar system, we identify the suitability of measured frequency spectrum for providing connectivity to the IoTs on the basis of SA. To the best of our knowledge, our study represents the first evaluation of more spectrum for the IoTs under SA in the radar spectrum.
- We propose the use of a Radio Environment Map (REM) architecture as an enabler to provide SA to the IoT networks in frequency channels used by different rotating radar systems. REM is a cognitive tool which can be utilized to enhance the awareness of the IoT entities of their operational radio environment [7].

It is important to note that our work in [8] presented measurement results for the spectrum usage of a weather radar in the 5GHz band. Different from [8], in this work we present results for three different rotating radar systems. Each of the measured radars is used for a different application, operates in a different spectrum band and has channel bandwidth utilization between 10 to 30 MHz (see Fig. 2, for

illustration). Moreover, different from [8], we identify the suitability of providing SA for the IoTs in the frequency channels used by rotating radar systems, and also propose the use of an REM architecture as an enabler to provide SA.

The rest of the paper is organized as follows: In Section II, we overview different IoT wireless technologies and their use of radio spectrum. In Section III, we present results of our measurement campaign, and also provide the reasons for the suitability of SA for the IoTs. In Section IV, we present a REM based SA framework. Finally, we conclude our work in Section V.

## II. DIFFERENT IOT WIRELESS TECHNOLOGIES AND THEIR USE OF RADIO SPECTRUM

Typically, the IoTs can generate different spectrum demands. Broadly speaking, based on radio range, the connectivity requirements of the IoTs can be roughly divided into two types as follows: 1) Low Power Wide Area Network (LPWAN) connectivity, which is particularly well-suited to the IoT applications that require a large number of widely dispersed devices to send occasional status updates and/or to be remotely activated, such as applications in connected gas and water utility meters [9]; 2) Low Power Short Range Network (LPSRN) connectivity, which is suited to the devices used in home automation, hospitals, and industries which can be connected to IoT using low power connectivity over short ranges of typically few hundred metres [10]. Based on service quality, they can be divided into three types: 1) Delay-tolerant IoTs; 2) Delay-sensitive IoTs; and 3) Delay-Intolerant IoTs.

In terms of spectrum usage, in general, there are three alternative tracks for the IoT services: 1) Licensed spectrum; 2) Unlicensed spectrum; and 3) SA spectrum. In Fig. 1, we highlight three different approaches that are either currently being used or are under consideration for use to meet the needs of different types of IoT services using unlicensed, and dedicated spectrum, along with the SA spectrum added.

### A. Licensed Spectrum and the IoTs

Cellular networks operate on licensed spectrum and are being rapidly evolved with new functionality and the new radio access technologies tailored to form an attractive solution for emerging low power wide area applications. Ericsson and Orange are testing EC-GSM (Extended Coverage GSM) using the 900 MHz licensed band, with the aim to enhance device reachability by up to 20 dB or seven-fold improvement in the range of low-rate applications. This extends the coverage of GSM to reach challenging locations such as deep indoor basements, where many smart meters are installed, or remote areas in which sensors are deployed for agriculture or infrastructure monitoring use cases. In addition, EC-GSM will reduce device complexity and thus lower costs, enabling large-scale IoT deployments. LTE for machine to machine (LTE-M) is another cellular IoT solution which utilizes the licensed spectrum and is based on LTE [11].

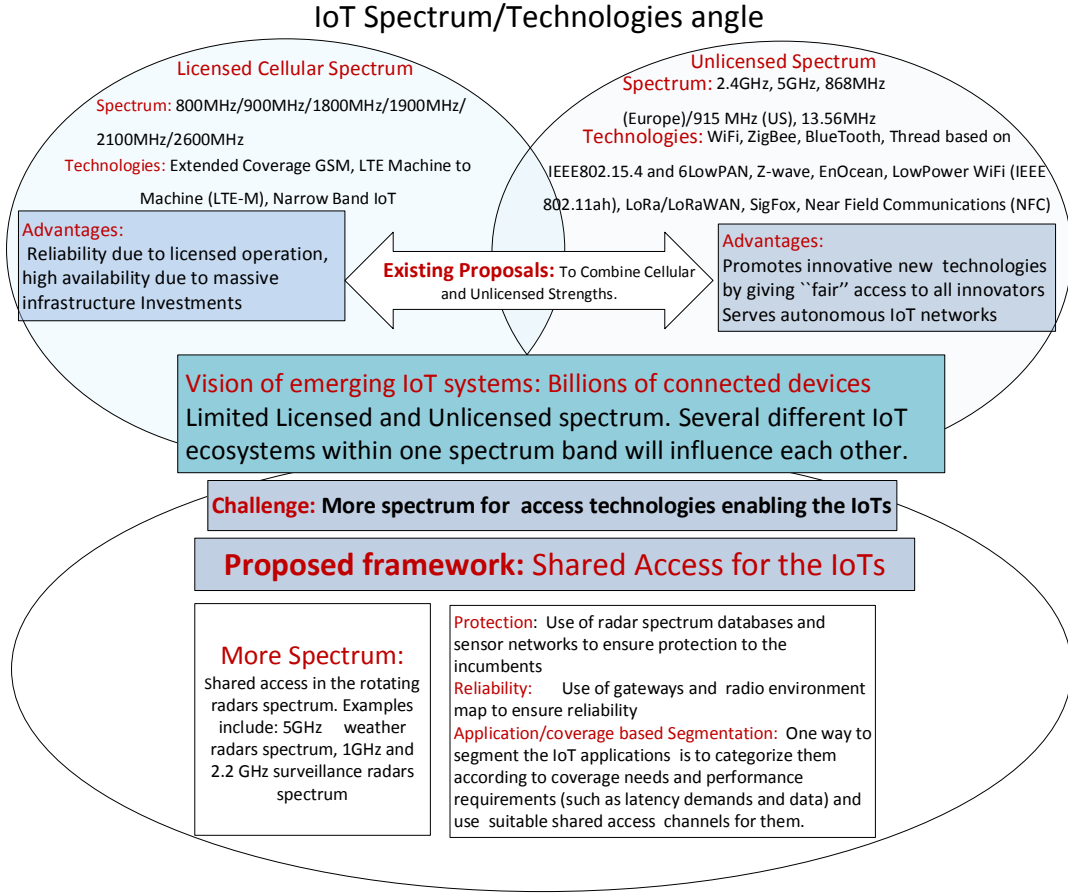


Fig. 1: Different wireless connectivity schemes for the IoTs and their spectrum usage.

### B. Unlicensed Spectrum and the IoTs

The WiFi alliance is working on a new IEEE 802.11ah standard which can manage LPWAN IoT devices. IEEE 802.11ah intends to operate over a set of unlicensed radio bands in the sub-1 GHz band. Some of the prominent features of the new IEEE 802.11ah are its energy saving mechanisms, its use of spectrum below 1 GHz ensures wider coverage for LPWAN IoTs. To power the IoT with new communication solutions independent IoT network groups have devised two different solutions for LPWANs which are called SigFOX and LoRaWAN. SigFox is a narrowband technology and uses a standard radio transmission method called binary phase-shift keying (BPSK). LoRaWAN looks at a wider amount of spectrum than SigFox [9]. Both LoRa and SigFox are planned to share spectrum with other solutions in the license-exempt bands.

### C. SA Spectrum and the IoTs

The IoTs (sensors, actuators, and gateways) are expected to produce unprecedented amounts of data, the collection, storage, and combined processing of which will become increasingly important [2]. The total

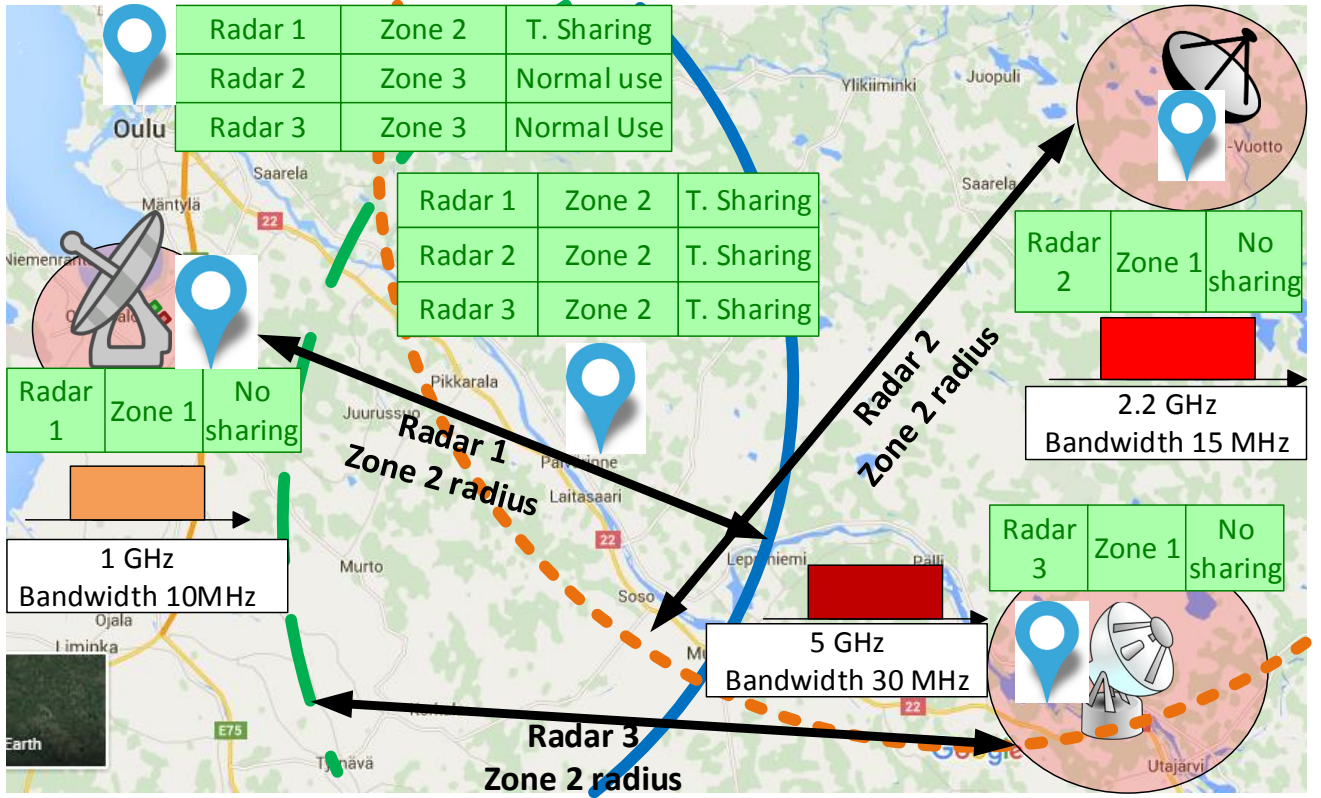


Fig. 2: Approximate locations, spectrum band utilization, bandwidth of each of the utilized channels, and different sharing zones at five different locations (blue location markers) for each of the three different radar systems measured by the authors. “T. Sharing” means temporal sharing.

demand of thousands of IoTs in a given area using heterogeneous access protocols can have significant effect on future radio spectrum use. The number of IoTs and the nature of traffic will thus require far more frequency spectrum than is commercially available for them today. In the context of making available more spectrum, the SA of wireless spectrum is an important and useful idea. The opening of TV White Spaces (TVWS) for wireless communications was one of the first initiatives relating to the SA spectrum. Ofcom in UK has already started putting in place the foundations to use TVWS for the IoTs. Shared spectrum access in TVWS as an enabler for the IoTs is also actively investigated by an IoT standard called Weightless [3].

Radar bands are now also a potential candidate for sharing between wireless communication systems and radar systems [5], [6]. In the next section, based on measurements of spectrum usage of different rotating radars, we will describe the suitability of rotating radar channels for the SA usage by the IoTs. Due to different radio range/service quality requirements, the spectrum bands that need to be considered for the IoTs should have wide variations in physical properties and utility to match the different IoT applications. In the next sections, we will also explain how the SA in rotating radar channels satisfy

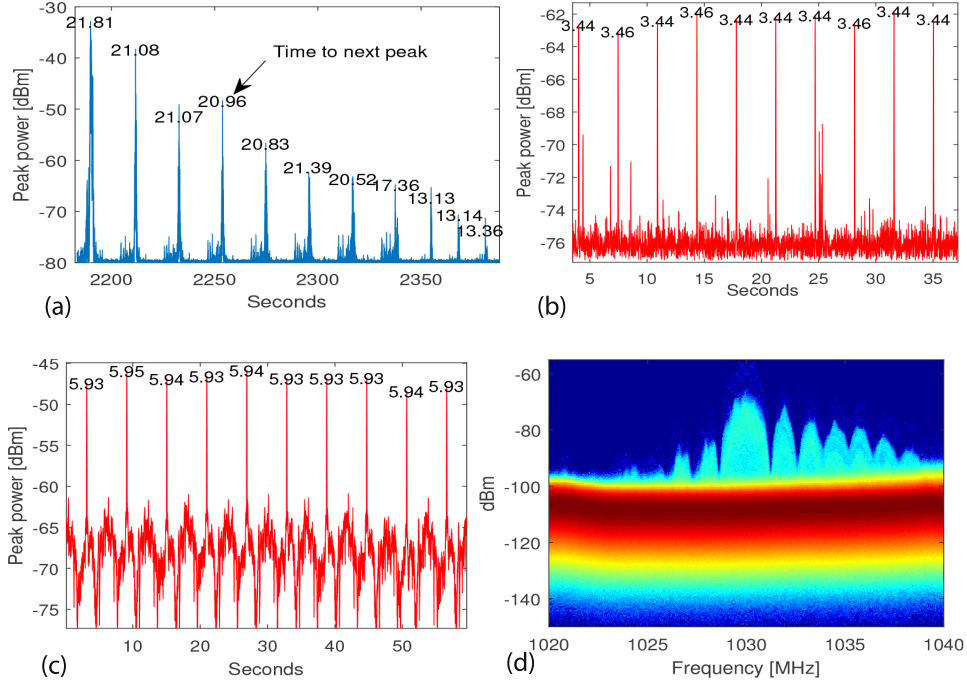


Fig. 3: Example measurement results showing the measured times between the main beam peaks of the three rotating radar systems, and the logarithmic two-dimensional spectrograms of the recorded power values of the airport surveillance radar signals.

this important need of the IoTs.

### III. MEASUREMENT RESULTS, ZONE-BASED SA, AND THE SUITABILITY OF THE SA FOR THE IOTs

#### A. Measurement Strategy, Setup, and Results

The rotating radars that operate in different bands have highly directional rotating antennas and provide coverage of applications over a large area (e.g., they can have a range of 150-200 km). The presented measurement results in this section include spectrum usage behavior of three ground-based fixed rotating radar systems in Finland: a weather radar system in the 5.6 GHz band, uplink of an airport aircraft surveillance radar system in the 1.03 GHz band, and a surveillance radar in the 2.3 GHz band. These radars transmit a narrow beam and they perform more listening than talking. For example, a weather radar may emit a pulse for  $2 \mu\text{s}$  then listen for approximately 2 ms. They rotate to scan horizontally 360 degrees, and some of them also tilt vertically. In Fig. 2, we illustrate approximate locations, spectrum band utilization, and the utilized channel bandwidths for each of the three different radar systems measured by the authors near the city of Oulu. Measurements were performed with an Agilent N6841A RF sensor connected to a wideband, omnidirectional antenna (ARA CMA-118/A) [12]. For both surveillance radars, the measurements were based on recording continuous (no time domain gaps) stream of I/Q samples. The sampling rate was (depending on the scenario) 2 MHz or 10 MHz, leading to the minimum time

resolution of  $0.5 \mu\text{s}$ . For weather radar case, measurements were based on recording continuous stream of FFT processed outputs (with 20 MHz sampling rate). Each measurement duration was more than 50 minutes at each location.

In Figs. 3a-3c, we present the measured times between main beam peaks of the three rotating radar systems operating in the three different spectrum bands. The three figures also illustrate the received peak power as a function of time in seconds. It can be seen in the three figures that there are pauses in the received signal from the radar, due to its antenna rotation. When the rotating radar's main scan beam points to the measurement locations, a signal peak is received. It can also be seen from the figures that while the radar's pulse interval, i.e., the time between two consecutive pulses received at the same location, are constant (Figs. 3b and 3c) for the measured surveillance radars, however, they are not constant for the weather radar. The pulse intervals of the radars in Figs. 3b and 3c are periodic with pauses of 3.44 and 5.93 seconds between the scan pulses, however, the pulse intervals of weather radar are quasi-periodic with pauses between the scan pulses that vary from 13.1 seconds to 21.1 seconds. This is due to the reason that the measured radar has two scanning modes: 1) The normal-mode with pulse repetition frequency (PRF) 570 Hz, pulse duration  $2 \mu\text{s}$ , rotation speed 16.9 degrees/s, lowest elevation angle 0.3 degrees. 2) The dual-mode with dual-PRF 900/1200 Hz, pulse duration  $0.8 \mu\text{s}$ , rotation speed 26.7 degrees/s, lowest elevation angle 0.4 degrees. Both normal and dual-polarization measurements are carried out by the radar, leading to varying rotation period.

Figs. 3a-3c also show that, while the received peak power for the two surveillance radars does not vary significantly, for the weather radar, the received power varies over a period of time. The reason for this received peak power variation is that unlike the two surveillance radars, the weather radar scans horizontally 360 degrees at different vertical angles. For the weather radar, the highest received peak power in Fig. 3a are obtained when the radar directs its beam downward to the measurement location. In Fig. 3d, we present logarithmic two-dimensional spectrograms of the recorded power values of the airport surveillance radar signals.

### B. Zone-based SA

Currently, the use of large geographical exclusion zones (between 72 and 121 kms) as a means for spectrum sharing with radar systems has been proposed in [5], [6]. Our measurement results show that there are pauses in the received signal from each of the three rotating radars, due to their antenna rotation (see Figs. 3a-3c). This offers the potential of low power IoT devices to use Zone-based SA in the radar bands [8], [13]. The Zone-based SA models have the potential of reducing the size of large exclusion zones around the rotating radar systems.

Zone-based SA models seek potential sharing opportunities both in the space and the time dimensions. Broadly speaking, a Zone-based SA model divides the area around a rotating radar into three zones, where the rotating radar itself is located at the centre of the zones (see Fig. 2). In Zone 1, opportunistic secondary operation is strictly forbidden as it can cause interference to the incumbent radar. In Zone 2, temporal sharing takes place, in which the users can transmit every time the radar's main beam is pointing in another direction. Finally, in Zone 3, the users are free to use the spectrum, as they are outside the interference area of the radar.

The potential of Zone-based SA or geographic exclusion zone based SA between radars and traditional wireless communication systems, such as small cell networks and WiFi networks, has been explored by [5], [13]. However, different works and reports have shown that existing sharing models either do not take into account the real spectrum usage of radar systems or they are often counter-productive to the goals of spectrum sharing in the radar bands [6]. In the next section, based on the analyzed features of different rotating radar systems, we will present a REM architecture as an enabler to provide SA for the IoTs.

### C. Reasons for Suitability of Zone-based SA, Implementation Challenges, and Spectrum Goodness

In Table I, we provide six reasons for the suitability of zone-based SA for the IoTs, and also present challenges involved in the implementation of SA in the radar channels. It is also important to identify which rotating radar channels are suitable for which IoT applications. For example, in a given area, a Zone 3 radar channel can be more suitable for applications that are intolerant to delays, whereas delay-tolerant applications can use a Zone 2 radar channel with little or no degradation in performance. In Table I, we also present spectrum goodness metrics that can be utilized for finding a suitable SA channel for an IoT application.

## IV. ENABLING IOT CONNECTIVITY THROUGH REMS

The general concept of REM was first introduced by [7]. In [7], REM is defined as a network entity which enhances the awareness of cognitive radios by providing them information about their radio environment. The provided information includes: device locations and their activities, policies and regulation to access spectrum, and other information.

### A. Role of the Gateways

In the proposed REM architecture (Fig. 4), the IoT gateways are used to act as a transparent bridge relaying messages between end-devices and an REM repository server in the back-end. Gateways that collect/transfer data wirelessly between small low-power IoT devices and cloud repositories via wireless



TABLE I: Six reasons for the zone-based SA suitability, implementation challenges, and spectrum goodness metrics for IoT applications

Features	Benefits for the operators providing IoT services	Challenges in implementation
Rotating radars operate in various spectrum bands, such as some weather radars in the 5 GHz and some surveillance radars in the 1 and 2 GHz bands.	i) In an area, long range IoTs can be served using the proposed SA in 1 and 2 GHz rotating radar channels, and short range IoTs in the 5 GHz rotating radar channels. ii) Different spectrum bands for long/short range IoT services can solve the potential problem of different IoTs influencing each other.	New models for SA which take into account: 1) real usage behavior and protection requirements of each rotating radar; 2) application requirements of different IoT services.
At a given location, there can be heterogeneous sharing zones due to distinct locations of radar systems (see Fig. 2, for example).	Some IoT applications are delay-tolerant while others are not. In a given area, an operator can allocate networks of delay-tolerant IoTs to the shared spectrum of Zone 2 radar, and delay-intolerant IoTs to the shared spectrum of Zone 3 radar.	i) Design of SA models that takes into account delay tolerance/delay intolerance of IoT applications. ii) Appropriate allocation design that assigns an IoT application to a suitable radar channel based on its delay requirement.
Surveillance radars with periodic scanning period	IoT networks located in Zone 2 of such radars can be served periodically.	i) Database assistance for any change in scanning pattern over longer periods. ii) Design of guard intervals before and after the main beam arrival ensures that the user does not interfere with the main beam pulse or with its side lobes.
Radars with quasi-periodic scanning periods	Quasi-periodic scanning radars, such as weather radars, have longer scan pulse intervals (between 13 to 22 seconds). Delay tolerant IoT networks that require longer interactions periods and are located in Zone 2 of such radars can be served quasi-periodically.	i) Regular database assistance for any change in scanning over shorter periods. ii) Design of longer guard intervals before and after the main beam arrival ensures that the user does not interfere with the main beam pulse or with its side lobes.
In general, radio navigation frequency reservations are almost similar across the globe.	Operators can have the possibility of designing unified standards under SA for the IoTs.	Coordination across different regulatory bodies across the globe.
Typically, single radar system per channel in an area with wide coverage areas (100 to 200 kms) and co-located transmitter/receiver.	Design of database assisted SA systems that require less interaction with the IoT networks.	Design of appropriate database technology.
Type of IoT application	Goodness metric	Explanation
Delay-tolerant	$B_f 1_{[f_{min} \leq f_a \leq f_{max}]}$	Amount of bandwidth $B_f$ the radar channel provides. The radar's channel frequency $f_a$ should lie within a certain range that is suited to the particular IoT applications' (long/short) radio range requirements.
Delay-sensitive (time important but not critical)	$B_f 1_{[f_{min} \leq f_a \leq f_{max}]}(d_0/d)$	Along with bandwidth $B_f$ and the frequency range satisfaction requirements, the IoT access should also take into account the desired time scale of packet arrival $d_0$ , and actual packet delay $d$ .
Delay-intolerant	$B_f 1_{[f_{min} \leq f_a \leq f_{max}]} 1_{[d < d_{max}]}$	Along with bandwidth $B_f$ and the frequency range satisfaction requirements, actual packet delays $d$ are not allowed to exceed the defined maximum delay $d_{max}$ .

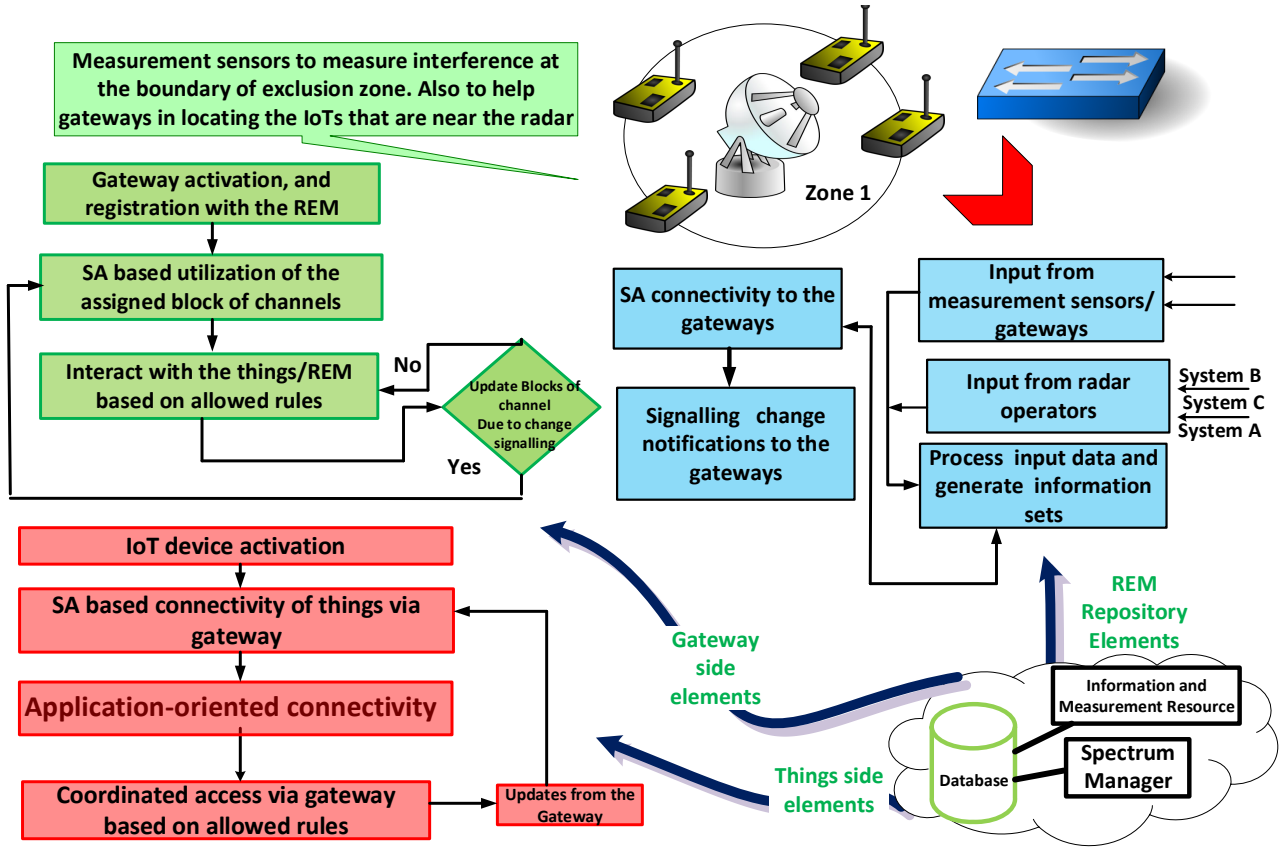


Fig. 4: Simplified high level block diagrams for different components involved in the proposed REM-based SA for the IoTs.

networks are essential. Although internet-connected smart phones and tablets can be used as gateways to collect/transfer data from/to IoT devices, for the IoT to encompass millions of devices, the gateways would be required to operate on a much larger scale. The gateways would require less human intervention to collect and transmit data. To this end, the gateways will be included in hubs for smart homes, into industrial equipment for purposes of tracking and asset management. In general, on one side, the gateways will communicate via wireless technology down-stream and up-stream with the small IoT devices. On the other side, the gateways will be wirelessly connected further upwards to the REM server.

### B. The Proposed Architecture

The proposed architecture can be divided into four components (see Fig. 4): 1) REM repository; 2) Different radar operators; 3) Measurement capable devices (MCD), such as a network of interference measurement and location estimation sensors, which are deployed at the boundary of a radar's exclusion zone; 4) IoT network entities, such as gateways and the IoT devices. In our proposed framework, the REM repository is a collection of resources that can be accessed by the IoT gateways. The REM repository consists of: 1) an Information and Measurement Resource Module (IMRM); 2) a database module (DM);

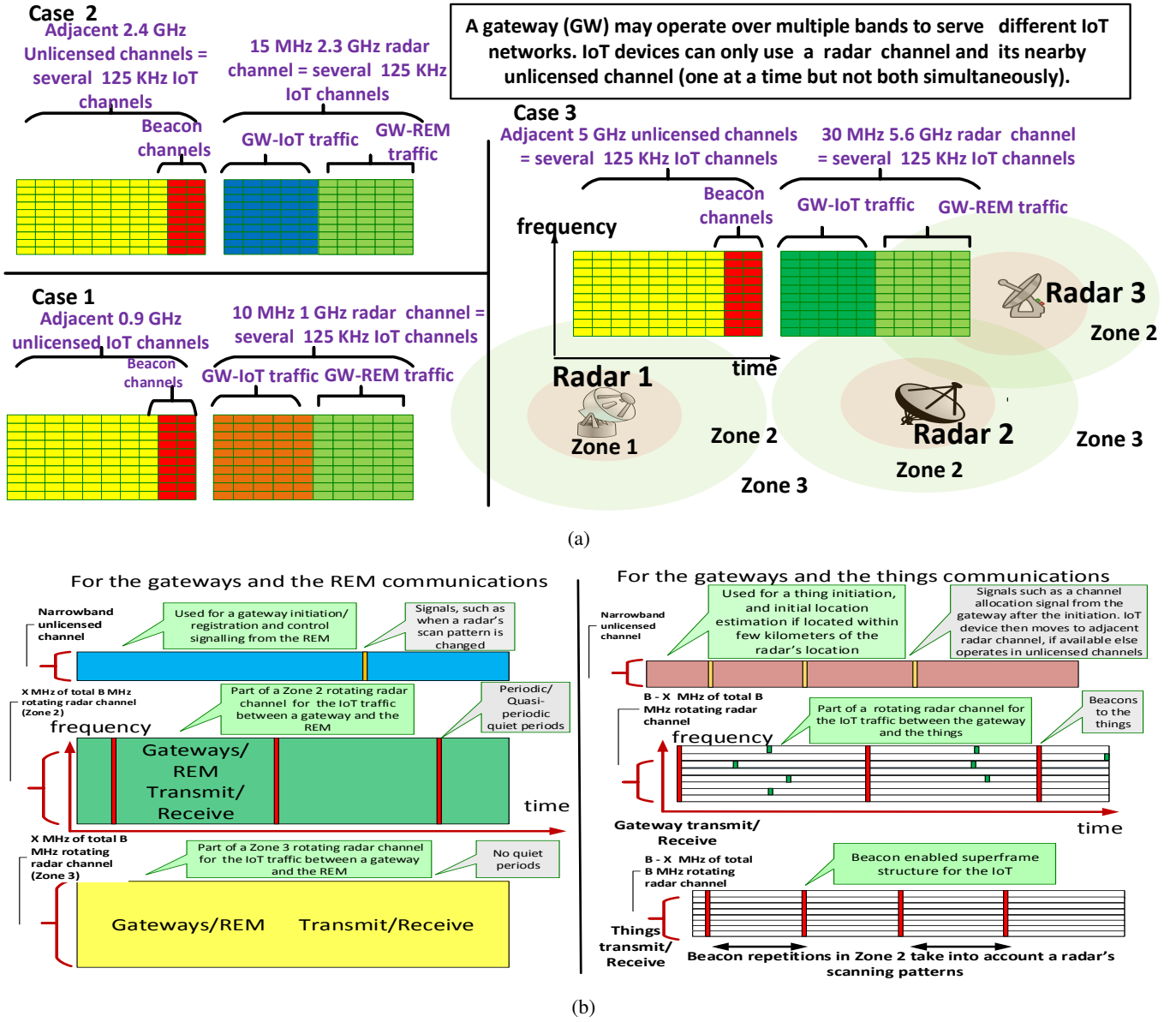


Fig. 5: Examples of beacon and traffic channel blocks for the proposed SA for the IoTs.

and 3) a spectrum manager (SM).

In Fig. 4 we present simplified high level block diagrams for different components involved in the proposed REM-based SA architecture for the IoTs. Next we explain the components of the proposed architecture.

### The REM repository elements

#### i) Information and Measurement Resource Module (IMRM):

- (Input from the radar operators) The IMRM module of the REM repository takes low-overhead static and dynamic information from different radar operators as input. *The static (one time) information includes:* 1) location of a radar system; 2) a particular radar system allows temporal sharing or not,

and an exclusion zone established by a regulatory body to prohibit secondary transmissions in a specific area around a radar; 3) a reference power threshold to ensure that a secondary network entity does not fall into the exclusion zone; 4) The rotation rate of a rotating radar. Also the time radar's rotating main beam spends at a reference point. *The dynamic information includes:* 1) Any change in scan speed of radar systems that are periodic/quasi-periodic rotating radars. Our measurement results show that weather radars can change their scan speed from fast to slow and also from slow to fast (see Fig. 3a). A low-overhead message using few bits can be utilized by a radar system operator to provide information about scan change notifications. Note that this does not require any changes in the operation of a radar system itself.

- *(Input from measurement sensors/gateways)*

- *Information about the radio environment:* The sensors collect information about the interference environment. For example, a sensor network deployed at the boundary of the Zone 1 of a radar can particularly facilitate interference free temporal sharing in Zone 2 with the radar. By deploying interference measurement sensors, an operator can know when and where the reference power threshold (defined by a regulatory body) is exceeded, if any, due to aggregate transmissions of the IoT entities. In the case of aggregate power received at the sensors exceeds the threshold, the REM repository instructs some of the gateways to move to another channel.
- *Location estimation of IoT devices near Zone 1:* The REM also uses the zone 1 sensors and the gateways (that are located near the Zone 1) to perform *sensor-gateway triangulation* for the location estimation of the IoT devices. When an IoT device is initiated, it listens for the Beacon signal from the nearby gateways on a Beacon channel (which is adjacent to the radar's channel), see Fig. 5 for illustrative examples. On hearing the Beacon signal it responds to it. The signal strengths between the IoT device and multiple sensors/gateways are measured; the signal strength indicates the distance from the sensor/gateway and a geometric calculation against other sensor/gateway locations is used to locate the device. If the device is within Zone 1 then it can only use unlicensed channels, else it can use the rotating radar channels adjacent to the unlicensed channels.

**ii) Database Module (DM):** The DM module processes information from the IMRM module and generates instruction sets for the IoT gateways operating in the area. Based on the processed information from IMRM, it lists channels that are available in an area for sharing, and also lists rules of sharing for a particular channel. It also stores the static information, the information from radar operators and/or sensors, which does not change over time, as well as recent instance of the dynamic information.

The instruction set generation at the DM provides a secure way of ensuring sharing with such radar

systems, as the access is controlled and managed by a trustworthy authority (cellular/IoT operator) which is authorized to operate in a given area by an official regulatory body.

**iii) Spectrum Manager (SM):** The SM on one side interacts with different gateways, such as it interacts with a gateway when its activated to collect its location information, and transmission power characteristics, and on the other side, it collects generated instructions from the DM. It then processes the obtained two-sided information and notifies the gateways about which portion of spectrum is available to them for utilization. When a radar channel is available, then the SM module provides rules of sharing for the channel, and also provides radar scan update notifications when the gateway is located in Zone 2. The SM module also notifies of moving to another channel when the channel becomes unavailable.

### The gateway elements

**i) Gateway activation/registration:** Depending on how many different applications it can serve, a gateway can operate over multiple bands or a single band. For example, if a gateway is deployed by a residential home, it may require only short range IoT connectivity, and hence may operate only in the higher 5 GHz bands. On the other hand, if a gateway is deployed by an operator to provide connectivity in a given area, it may be required to provide long range and/or short range connectivity to a variety of different IoT applications. Hence, it may be required to operate over multiple bands.

When activated, a gateway, in order to obtain channel access authorization, needs first to register with the SM module. This procedure can be carried out as follows: an unlicensed channel adjacent to a rotating radar channel is partitioned into several subchannels of 125 KHz bandwidth. A small set of these subchannels, called beacon channels, is used for the beacon transmissions (see Fig. 5). On activation, a gateway first listens to one of these beacon channels and registers with the REM repository. The registration of a gateway involves providing its location information, and transmission power characteristics in order for the list of available/forbidden channels to be computed.

**ii) SA based utilization of the channels:** The gateway obtains from the REM repository a list of available channels, which is a set of unlicensed channels and available radar channels, and also obtains the rules for sharing in each of the available channels. Each of the available unlicensed/radar channels, whose bandwidth may vary between 10-30 MHz, is partitioned into several subchannels of 125 KHz bandwidth. A set of these subchannels is utilized by the gateway to communicate with the REM repository, and the other subchannels are utilized to communicate with the IoT devices (see Fig. 5 for illustrative examples).

### The things elements

At a given time, an IoT device can operate only over a single radar channel or an adjacent unlicensed channel but not both. Each gateway continuously transmits information, such as its identification number

(ID), on the beacon unlicensed channels adjacent to the radar channels on which it can operate. When the signal is picked up by a nearby IoT device, which is just initiated, it responds to the signal. The gateway selects a set of subchannels for exchanging traffic with the IoT device. When the radar channel is not available in the area the gateway selects this subchannel set from the unlicensed channel adjacent to the radar channel, otherwise it selects the set from the radar channel.

On a radar channel, the communication format consists of a periodic/quasi-periodic superframe. The superframe starts with a beacon signal transmitted by a gateway (See the beacon signals on the right of the Fig. 5b). More than one gateway in an area can transmit beacon messages at the same time and avoid interference by using a spread spectrum radio modulation used in existing IoT protocol like LoRaWAN [9]. The beacon signal notifies the IoT devices about the beacon repetition rate, i.e., when to listen for the next beacon, communication period message which notifies the length of the period after the beacon signal during which the devices can transmit/receive their traffic (for the illustration, see Fig. 5b).

In a Zone 3 radar channel, the superframe duration can be adjusted to any length suitable for the network. In a Zone 2 periodic radar channel, such as the radars in the 1 GHz and the 2.3 GHz, the beacon can be transmitted to the devices after the radar's main beam leaves the slice in which the network is located. The network stays quiet during the time the radar's main beam spends on the slice  $T_s$  and also during the guard intervals time  $T_g$  before and after that slice. This means that if the radar's main beam points every  $T_r$  seconds at the slice, then a superframe of length  $T_r - T_s - 2T_g$  can be utilized for the IoT traffic. For example, with  $T_s = T_g = 0.5$  seconds this can be equal to  $T_r - 1.5$  seconds.

In a Zone 2 quasi-periodic radar channel, such as the radar in the 5 GHz (see Fig. 3a), the time  $T_r$  can vary over different periods. To take into account of this quasi-periodicity due to the slow scan mode and the fast scan modes of the radar, the length of the superframe can be set to be  $\min(T_r) - T_s - 2T_g$  for the IoT traffic. For example, in the case of the weather radar results in Fig. 3a show that the  $T_r$  varies from 13.13 seconds to 22 seconds. With  $T_s = T_g = 0.5$  seconds, the superframe length can be equal to  $13.13 - 1.5 = 12.13$  seconds. The gateway can transmit a beacon after the radar's main beam leaves the slice in which the network is located. The superframe lasts 12.13 seconds followed by the quiet period. The devices listen to the next beacon at the specific time period (the time indicated in the previous beacon). In case the radar changes the scan mode in a way that the next beacon coincides with the main beam the beacon is not transmitted and hence not received. The IoTs then listen for no more than  $\max(T_r)$  seconds to get synchronized with the next beacon again. For the measured weather radar  $\max(T_r) = 22$  seconds.

## V. CONCLUSIONS AND FUTURE DIRECTIONS

Radar bands are a potential candidate for spectrum sharing between wireless communications and incumbent systems. To better understand the operating principles of various rotating radars which operate in different spectrum bands, and to determine their spectrum usage patterns, we ran an extensive measurement campaign near the city of Oulu in Finland. During the campaign, the spectrum usage behavior of three ground-based fixed rotating radar systems at different locations was measured. Based on the measurement results, in this paper, we identify the suitability of the rotating radar spectrum for the IoT shared spectrum access. We present reasons for the proposed SA suitability, identify related implementation challenges, and discuss spectrum goodness metrics for IoT applications. We also propose a framework that enables SA for the IoTs through REMs. For potential future work, this research can be extended to explore the challenges in the implementation of the proposed REM-based SA in the rotating radar's channels. Challenges such as the required number of measurement sensors to support the REM, update rate of the REM, its algorithmic complexity, and security issues. The prototype can also be developed to enable SA through REMs for the IoT connectivity.

## REFERENCES

- [1] European Union, "Report on Collective Use of Spectrum (CUS) and other spectrum sharing approaches," Radio Spectrum Policy Group, Tech. Rep., 2011. [Online]. Available: {<http://rspg-spectrum.eu/wp-content/uploads/2013/05>}
- [2] H. R. Schindler, J. Cave, N. Robinson, V. Horvath, P. J. Hackett, S. Gunashekar, M. Botterman, S. Forge, and H. Graux, "Europe's policy options for a dynamic and trustworthy development of the Internet of Things," Tech. Rep., 2013.
- [3] S. Forge, "Radio spectrum for the internet of things," Tech. Rep., 2016. [Online]. Available: {<http://www.emeraldinsight.com/doi/abs/10.1108/info-11-2015-0050>}
- [4] Federal Communications Commission, "Enabling Innovative Small Cell Use In 3.5 GHz Band NPRM & Order," *Docket 12-148*, 2012.
- [5] CSMAC Committee, "Interference and Dynamic Spectrum Access," National Telecommunications and Information Administration (NTIA), USA, Tech. Rep., November, 2010. [Online]. Available: {<http://www.ntia.doc.gov/legacy/advisory/spectrum/reports>}
- [6] M. Cotton, M. Maior, F. Sanders, E. Nelson, and D. Sicker. (March, 2012) Developing Forward Thinking Rules and Processes to Fully Exploit Spectrum Resources: An Evaluation of Radar Spectrum Use and Management. [Online]. Available: {<http://www.its.bldrdoc.gov/publications/2669.aspx>}
- [7] Y. Zhao, "Enabling cognitive radios through radio environment maps," Ph.D. dissertation, Virginia Tech, USA, 2007.
- [8] Z. Khan, J. J. Lehtomäki, R. Vuontoniemi, E. Hossain, and L. A. DaSilva, "On opportunistic spectrum access in radar bands: Lessons learned from measurement of weather radar signals," *IEEE Wireless Communications Magazine*, pp. 1–15, 2016, in press.
- [9] Technical Marketing Workgroup, "LoRaWAN: What is it?" LoRa Alliance, Tech. Rep., 2015.
- [10] M. Andersson, "Short range low power wireless devices and Internet of Things (IoT)," U-Blox, Tech. Rep., 2015.
- [11] Nokia, "LTE-M: Optimizing LTE for the Internet of Things," White Paper , Tech. Rep., 2015.
- [12] Agilent Technologies, "Agilent radar measurements," Application Note, Tech. Rep., 2014.
- [13] M. Tercero, K. Sung, and J. Zander, "Temporal secondary access opportunities for WLAN in radar bands," in *Proceedings of the 14th International Symposium on Wireless Personal Multimedia Communications (WPMC)*, 2011, pp. 1–5.